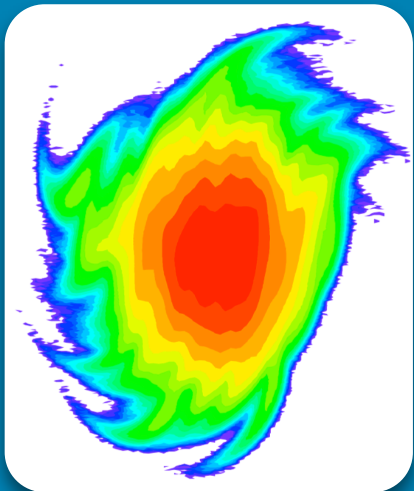
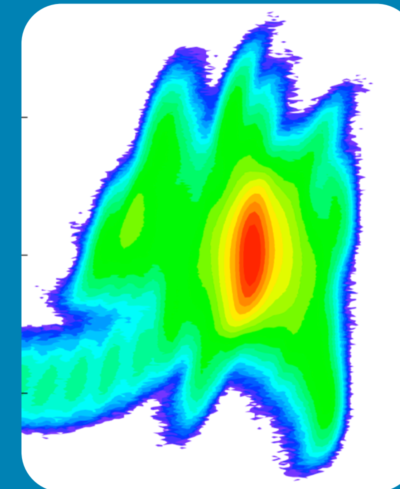


# HOM coupler requirements for SPL/SNS/ESS



F. Gerigk, CERN

Project X collaboration meeting, 12-14 April 2011, ORNL

based on the PhD studies by M. Schuh (now at KIT, Karlsruhe, Germany)

# Disclaimer

- M. Schuh (CERN doctoral student) has studied in depth the HOM damping needs for the SPL and developed the code SMD (**S**imulate higher order **M**ode **D**ynamics).
- He could explain why SNS does not need HOM dampers.
- For ESS a comparison was made between a 1300 MHz linac and a 704 MHz linac, covering the same energy range. However, no complete study of HOM needs for ESS was done by us!

# Overview

- Transverse effects/longitudinal effects
- General observations
- Beam chopping
- HOM power dissipation
- Excitation of fundamental passband modes
- Consequences for SPL/SNS/ESS

# transverse effects

- HOMs that affect the transverse plane (e.g. Dipole modes) are excited by off-axis beams.
- However, with $Q_{ex} = 10^7$, even offsets of several mm, induce only negligible HOM cavity voltages (kV) and negligible increases of the effective beam emittance (<10% on ML).

| | Mean | σ |
|---|---|---|
| $f_{Dipole}$ (β=0.65/1.0) | 1020/915 MHz | 1 MHz |
| $I_{beam}$ | 400 mA | 3% |
| $(R/Q)_{\perp,max}$ (β=0.65/1.0) | 103/57 Ω | |
| $T_{pulse}$ | 1 ms | |
| $f_{rep}$ | 50 Hz | |

$$(R/Q)_{\parallel,n}(\beta) = \frac{\left| \int_{-\infty}^{\infty} E_{n,z}(r=0,z) e^{i\omega_n \frac{z}{\beta c}} dz \right|^2}{\omega_n W}$$

$$(R/Q)_{\perp,n}(\beta) = \frac{ic}{\omega_n x_0} \frac{\left| \int_{-\infty}^{\infty} E_{n,z}(r=x_0,z) e^{i\omega_n \frac{z}{\beta c}} dz \right|^2}{\omega_n W}$$

# longitudinal effects

- proton linacs span a wide range of particle velocities,
  - ➡ voltage errors yield phase errors, which yield larger voltage errors, etc.
  - ➡ (R/Q) of the accelerating mode and the HOMs depends on the velocity,
- chopping creates new machine lines,

# general findings

| Effect | typical value | Longitudinal | Transversal |
|---|---|---|---|
| HOM Frequency Spread | 1 MHz (σ) | ↘ | ↘ |
| Machine Lines | - | ↗ | → |
| I · R/Q | - | ↗ | ↗ |
| Charge Scatter | 3% | ↗ | → |
| Chopping | 3/8 - 300/800 | ↗ | ↗ (bunch charge) |
| Passband Modes | - | ↗ (Chopping) | - |
| RF-Errors | 0.5°/0.5% (rms) | → (on HOM) | - |

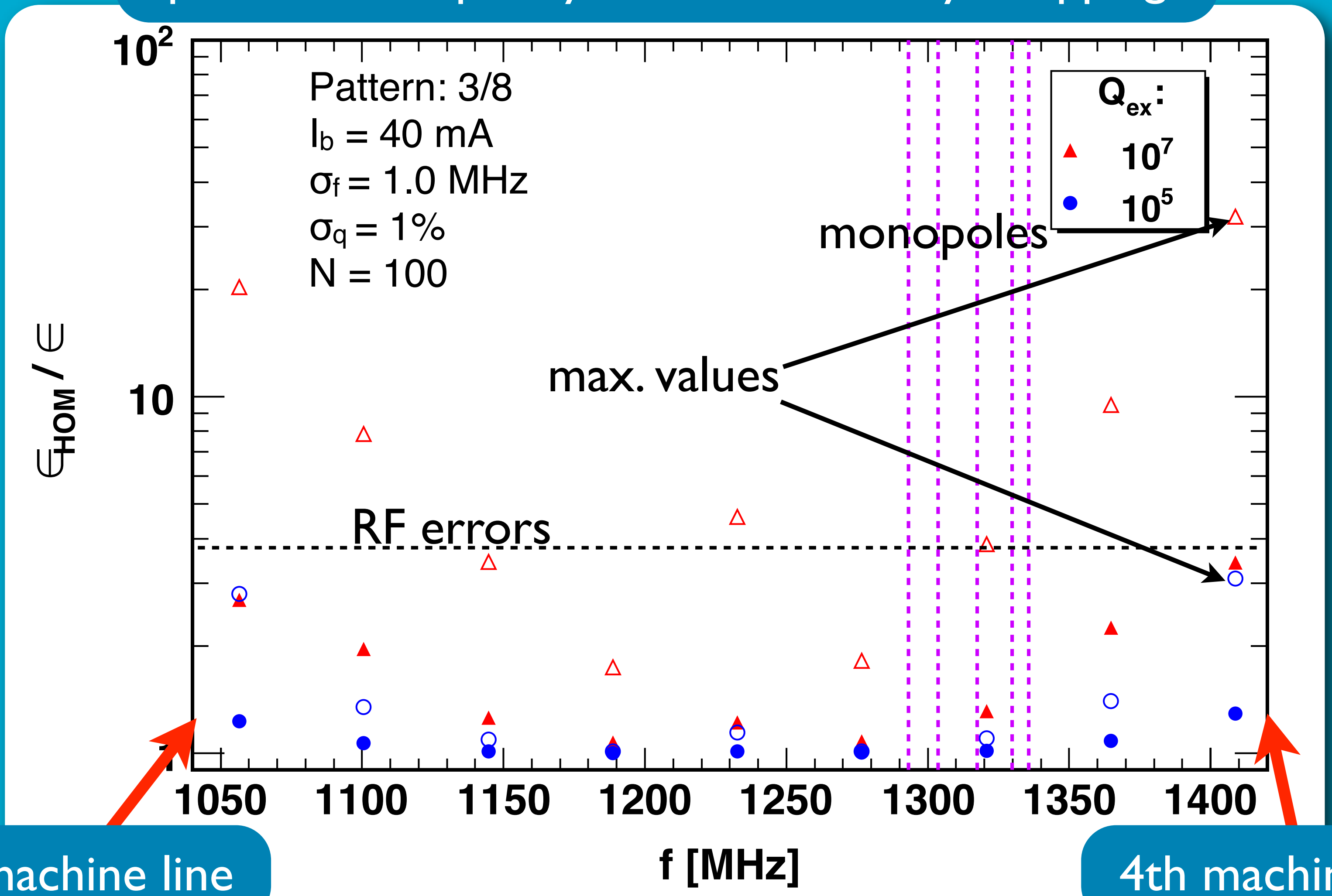
M. Schuh et al: "Influence of Higher Order Modes on the Beam Stability in a High Power Superconducting Proton Linac", submitted to PRSTAB

# general findings

- We can excite HOMs at any frequencies, not only when they coincide with machine lines!
- However, outside of machine lines ($\Delta f$ > 3 MHz), with a HOM frequency spread > 0.1 MHz, and with a charge scatter <5%, the effects of HOMs ($Q_{ex} = 10^7$, I=400 mA) are buried within the noise created by the RF system (0.5°/0.5% rms).
  - ➡ We use the effective emittance increase of a pulse, which is caused by RF errors as threshold.
  - ➡ If we can keep a distance of 3 MHz between HOMs and machine lines, we do not see a disturbance of the beam.

# beam chopping

put HOM frequency on ML created by chopping



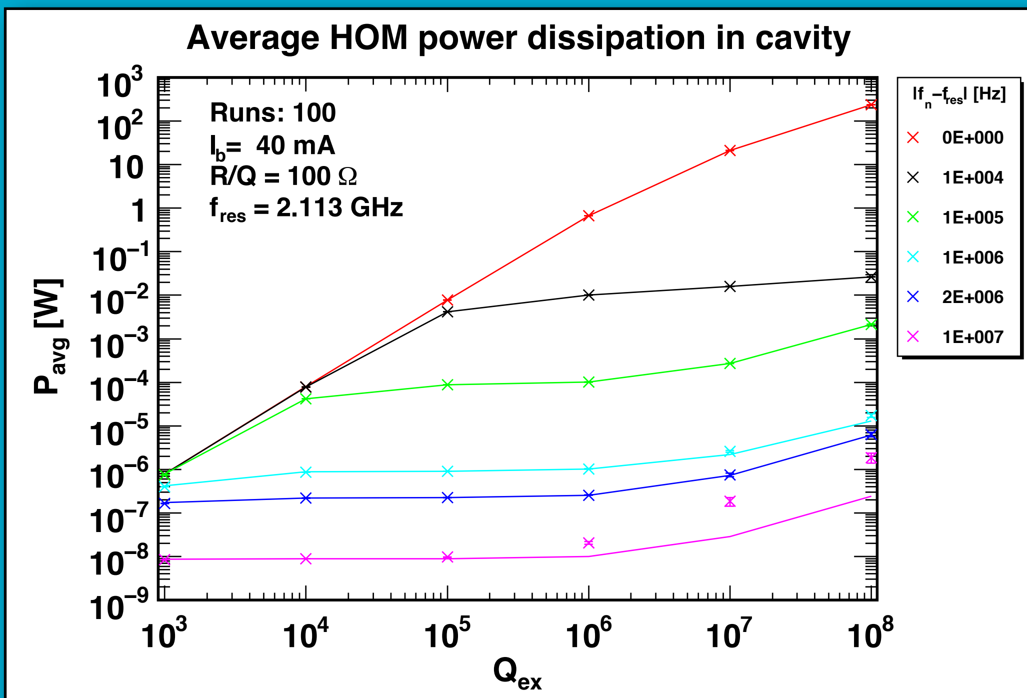

3d machine line

4th machine line

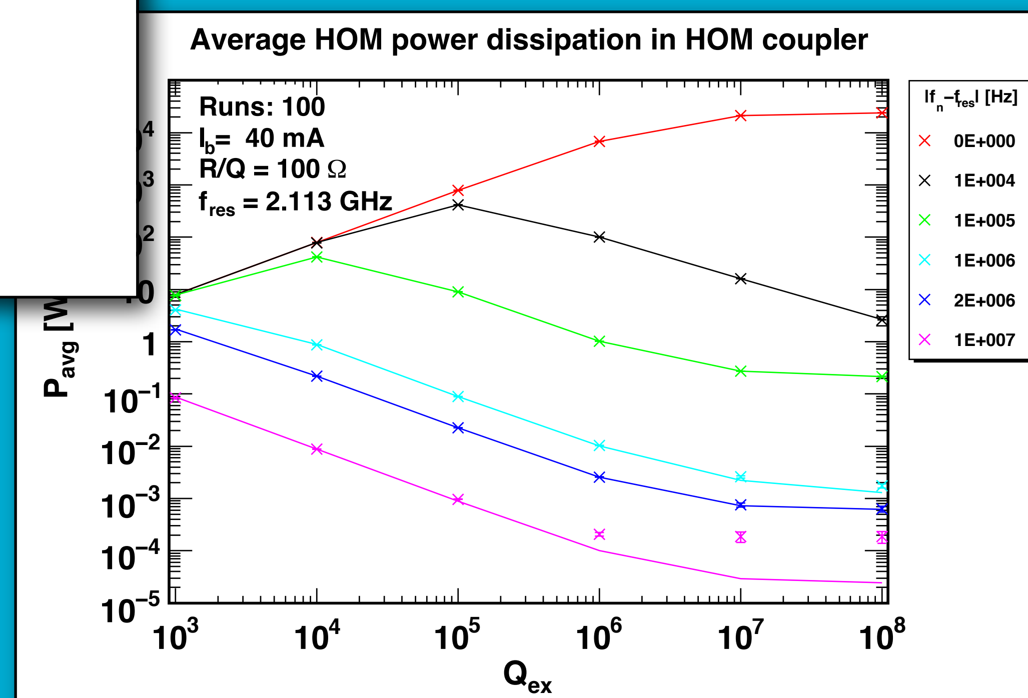
# beam chopping: conclusions

- any pulse sub-structure creates new machine lines,
- only high-frequency chopping patterns (e.g. 3 empty bunches out of 8) create important machine lines,
- if we want to allow all possible chopping patterns, then in the SPL case we need to impose a maximum $Q_{ex}$ ($10^5$) for all HOMs,
- lower frequency patterns (e.g.30/80 or 300/800) do not have a significant influence,

# HOM power




Beam noise:
- $\sigma_q = 1\%$
- $\sigma_\varphi \approx 0.4$ ps (not const. during pulse)



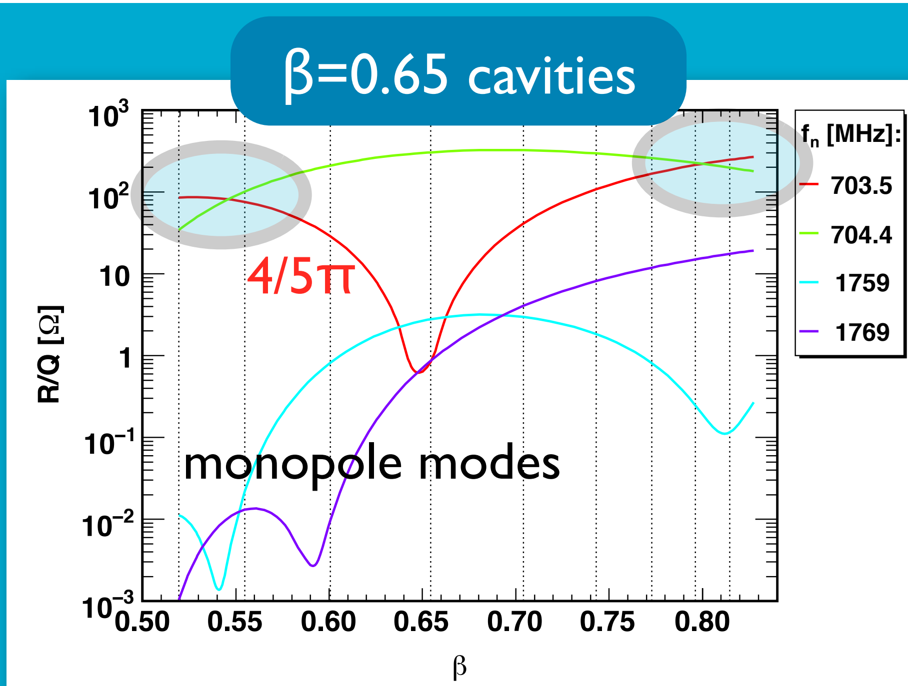

The limitation may come from the power extracted by the coupler, rather than the dissipated power in the cavity.

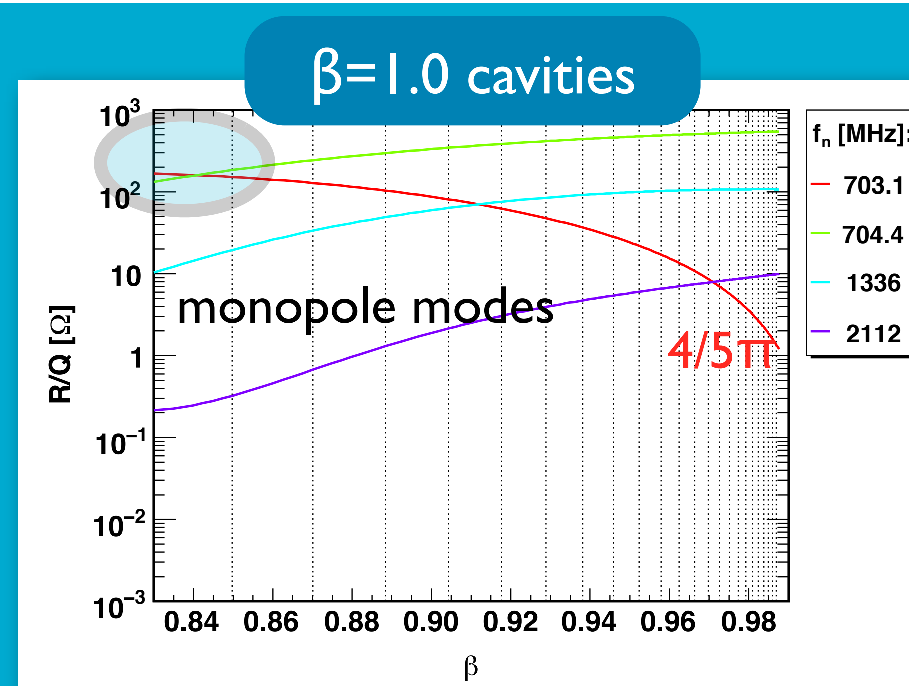
# HOM power: conclusions

- ***On fundamental machine line***: 1W dissipated power in the cavity needs a $Q_{ex}$ of ~$10^6$. However for the, 100 W extracted HOM power needs a $Q_{ex}$ of $10^4$ (1 kW ~ $10^5$). **Alternatively** ensure >100 kHz distance of HOM to resonance line.
- ***On chopping machine line (high frequent):*** 1W dissipated power in cavity: $Q_{ex}$ ~2-3 $10^6$. 100 W extracted HOM power: $Q_{ex}$ ~$10^5$. **Alternatively** ensure > 10 kHz distance of HOM to resonance.

M. Schuh, W. Weingarten: "Power dissipation by Higher Order Modes", CERN-sLHC-Project-Note-0027

# Fundamental passband modes (FPM)

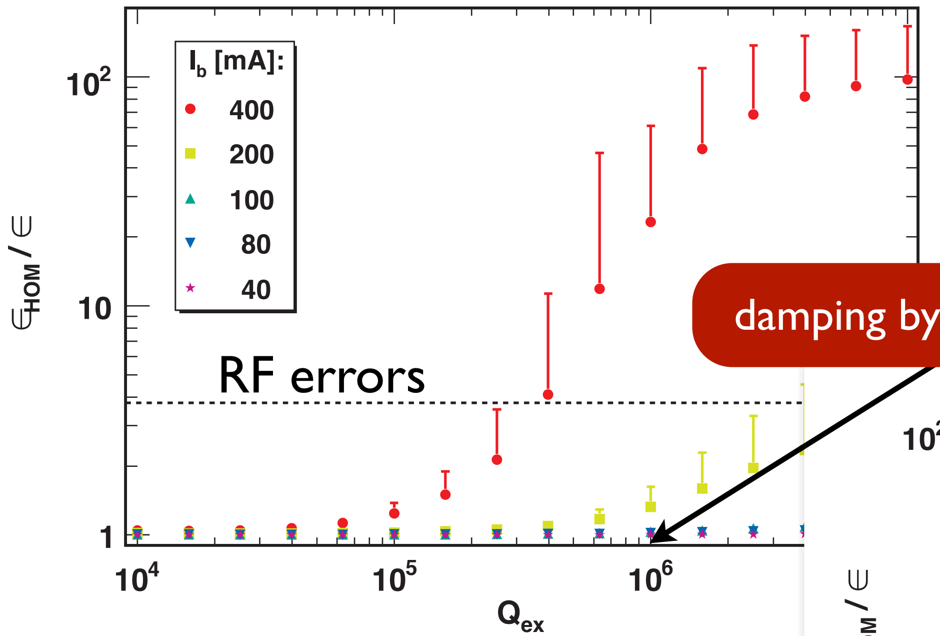



- The 4/5 π mode can have significant (R/Q) values, even exceeding those of the accelerating mode.

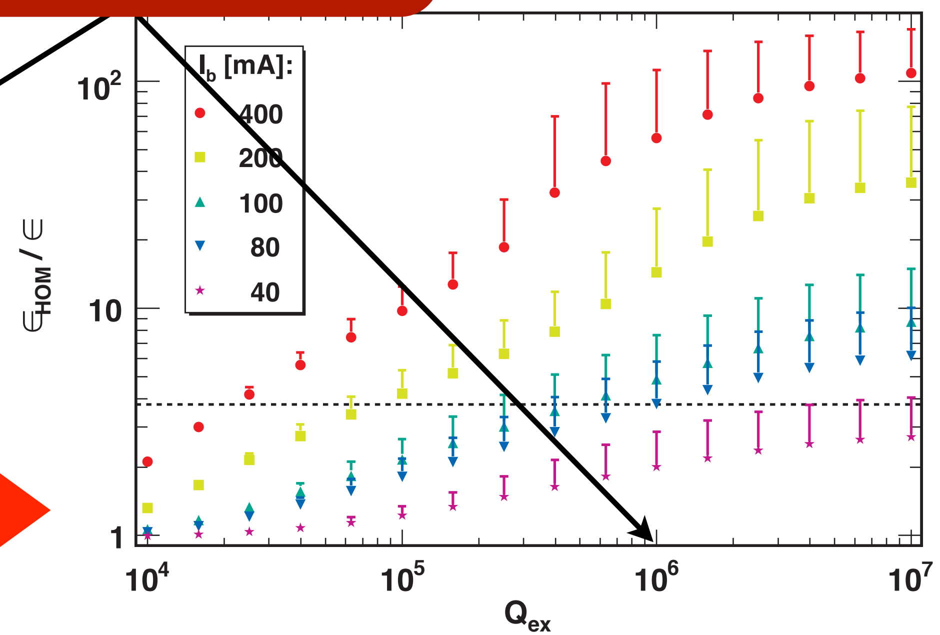
# FPMs II

effective phase space increase of pulse




- frequency spread: 10 kHz,
- charge scatter: 3%

damping by power coupler




- directly on a 30/80 chopping machine line

# FPM: conclusions

- Depending on the linac layout, FPMs can be excited to significant levels and disturb the beam.
- In the SPL case the 4/5 π mode is damped by the power coupler with $Q_{ex} \approx 10^6$.
- An optimization of transition energies is certainly helpful (e.g. start at 180 MeV instead of 160, and use a $\beta<1$ cavity for the high-energy part.
- The choice of transition energies and cavity βs has a big influence not only on the FPM but also on the HOMs (β dependency of (R/Q).

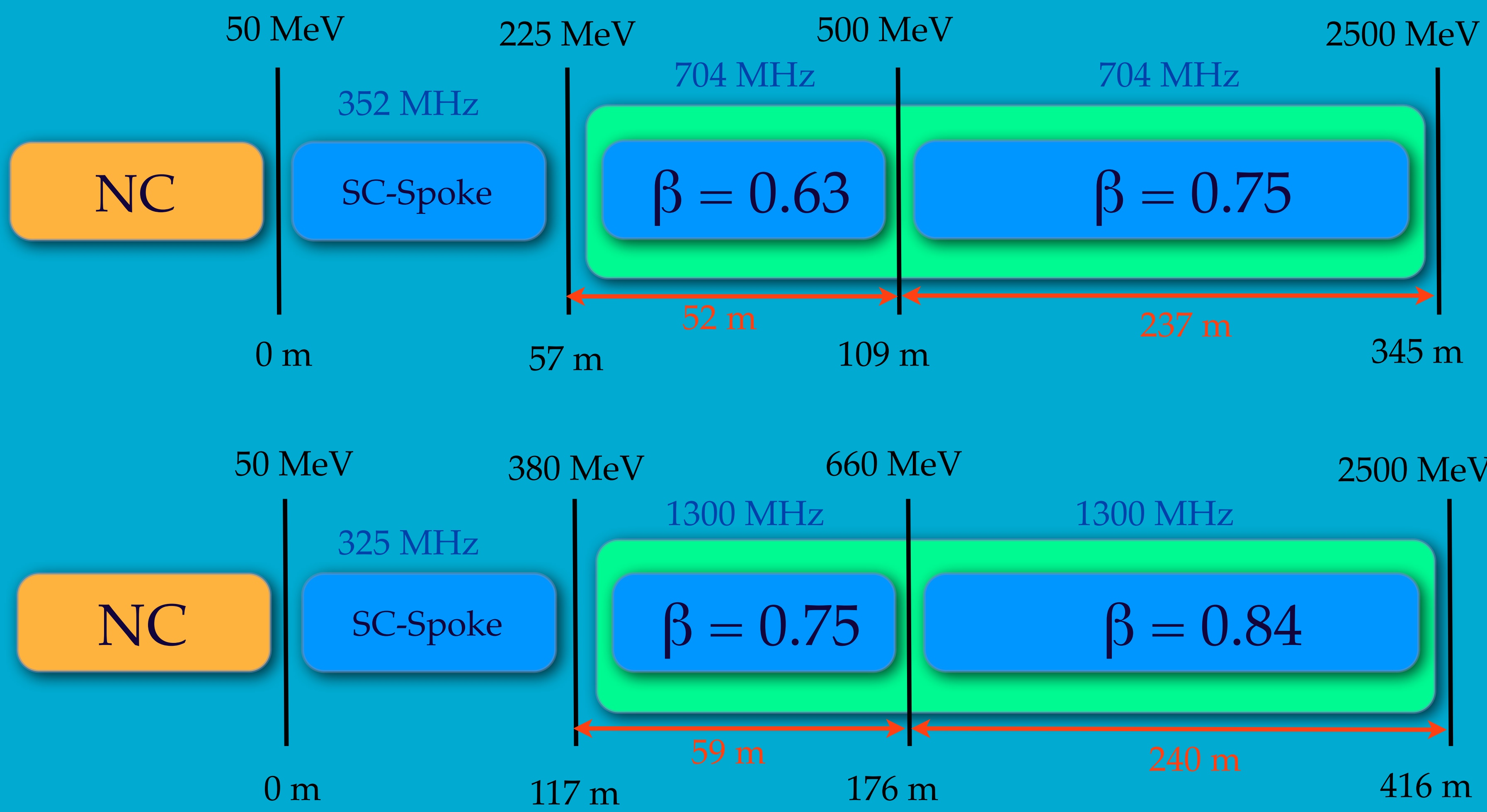
# Why can SNS take out their HOM couplers?

| | SPL | SNS |
|---|---|---|
| Chopping | 3/8 or similar (high-frequency) | 118/378 (low frequency) |
| No Cavities | 250 | 81 |
| HOM Frequencies | not measured | none close to machine lines (known) |
| Max $(R/Q)_{HOM}/(R/Q)_{acc}$ | 6%/20%† | 2%/7% |
| Max $(R/Q)_{PBM}/(R/Q)_{acc}$ | 83%/31%‡ | 46%/27% |

† lower max. $(R/Q)_{HOM}$ values seem to be a feature of low-β cavities, not well understood.

‡ depends on the β-range per cavity type.

# ESS frequency comparison

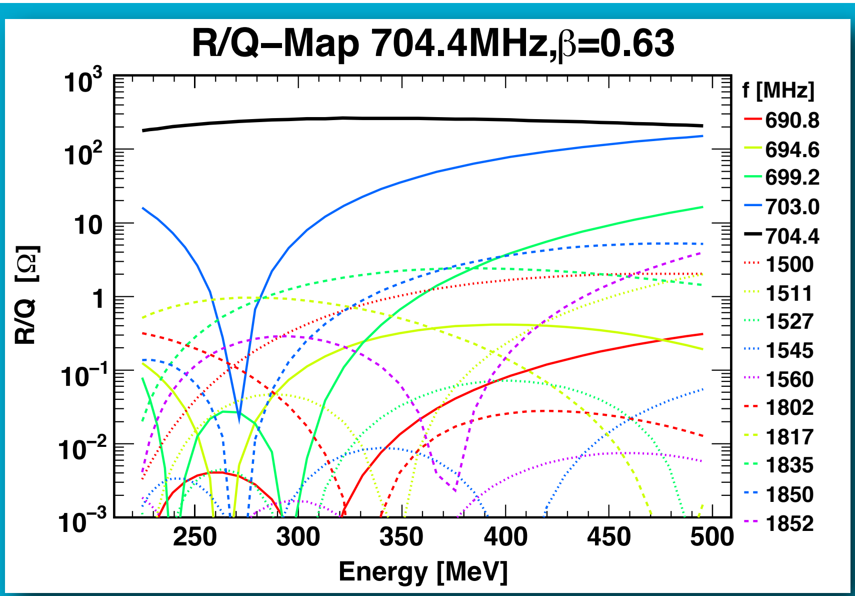


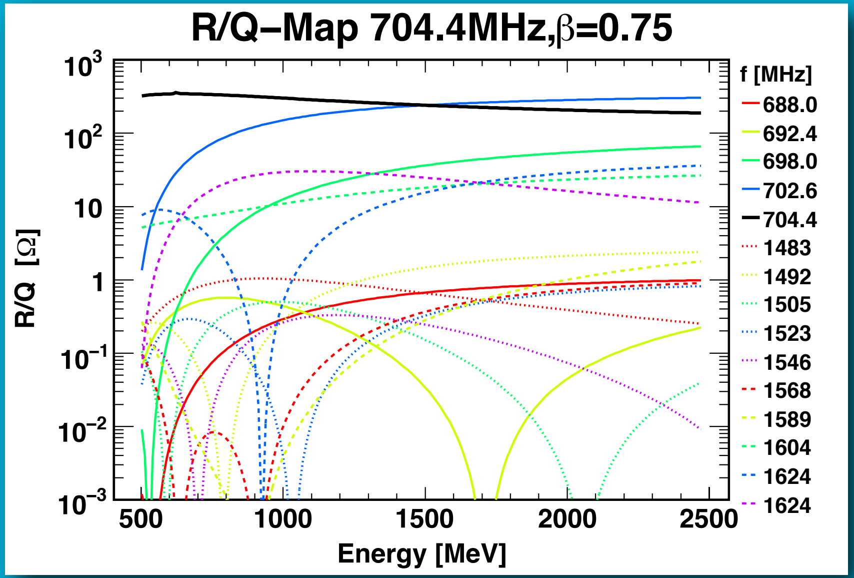

M. Schuh: "HOM Issues in 704.4 MHz and 1.3 GHz superconducting cavities", CERN-sLHC-Project-Note-0031

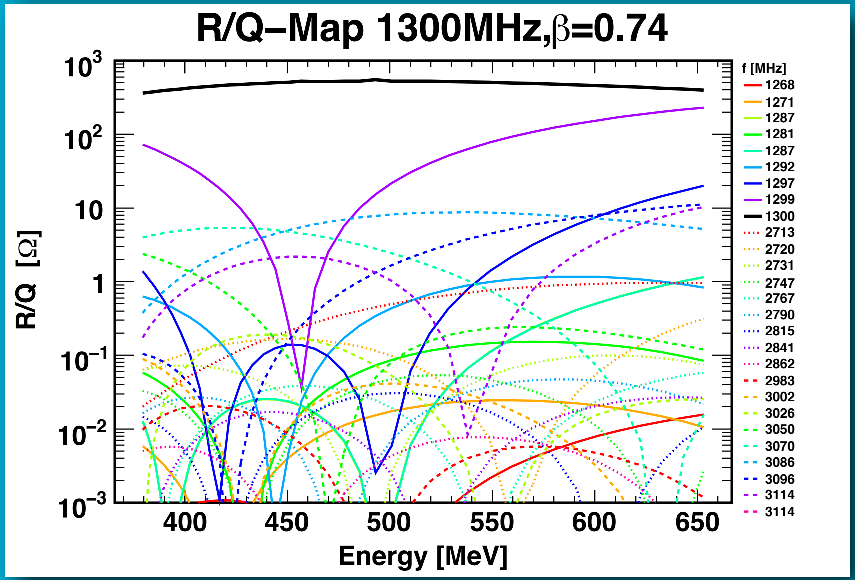
# cavity data

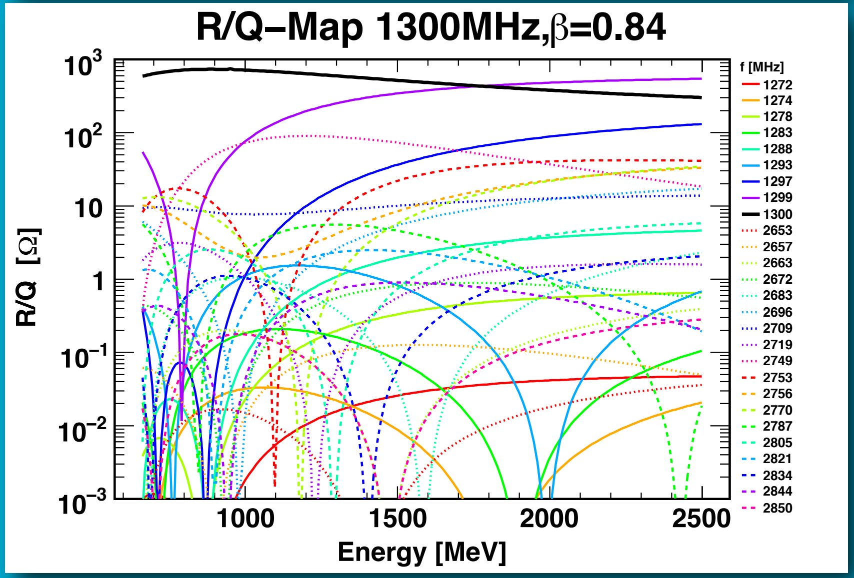
| | 704.4 MHz | | 1.3 GHz | |
|---|---|---|---|---|
| $\beta_g$ | 0.63 | 0.75 | 0.74 | 0.84 |
| Cells | 5 | 5 | 9 | 9 |
| L ($L_{active}$) [m] | 0.99 (0.67) | 1.11 (0.79) | 1.09 (0.77) | 1.19 (0.87) |
| $R_{iris}$ [cm] | 5.5 | 6.2 | 3.5 | 3.5 |
| R/Q($\beta_g$) [$\Omega^\dagger$] | 238 | 307 | 513 | 715 |
| Gradient [MV/m] | 14 | 20 | 15 | 21 |
| $f_{Cutoff}$ [GHz] | 2.09 | 1.85 | 3.28 | 3.28 |
| Installed | 36 | 168 | 40 | 160 |

# (R/Q) of FPMs and HOMs

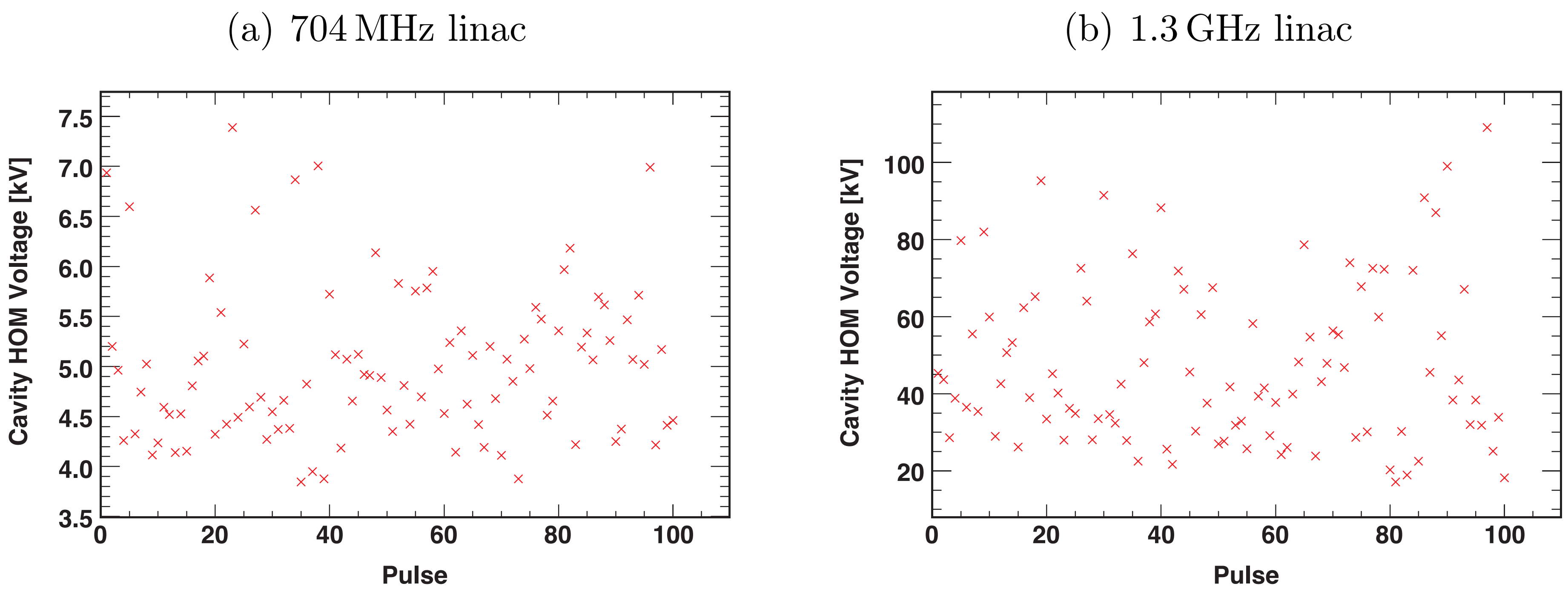


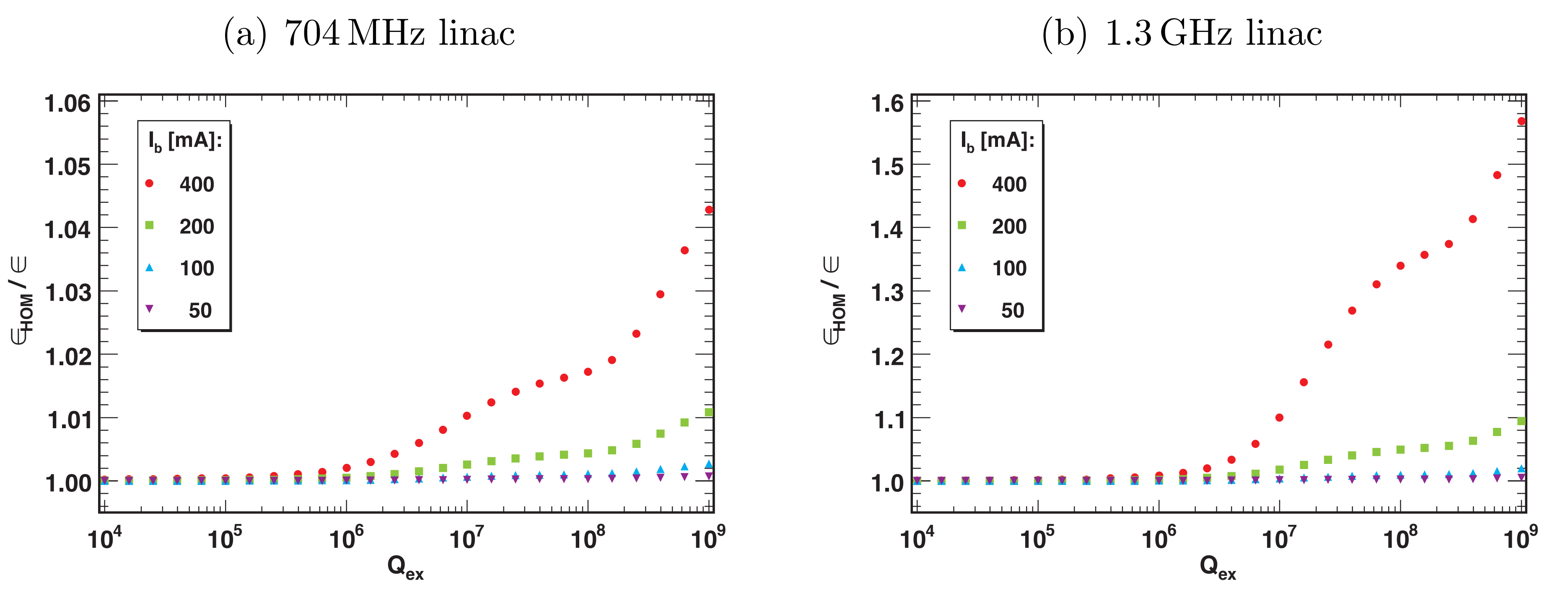



# induced HOM voltages



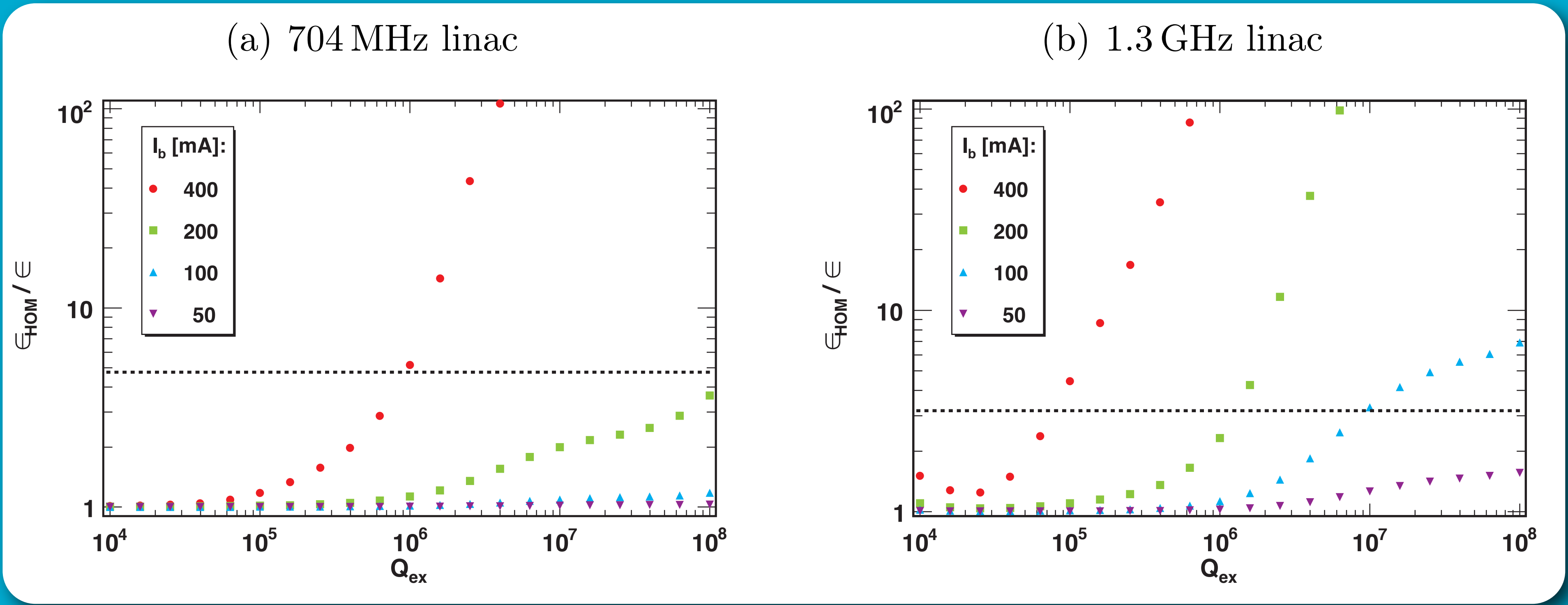

Voltages after one pulse (averaged over 100 pulses) at 400 mA, $Q_{ex}=10^8$ assuming the presence of the most prominent HOMs.

# effective (pulse) emittance growth




At 50 mA there is no measurable effect for $Q_{ex} < 10^8$ in both cases.

# excitation of FPMs ($TM_{010}$)




influence of neighboring FPMs at the end of one pulse

# Conclusions of frequency comparison

- For both simulated linac sections a $Q_{ex} = 10^8$ seems sufficient, when staying away from machine lines and operating at 50 mA.
- HOM voltage maxima in the 1.3 GHz case are ~10 times higher.
- Effective growth (pulse) in the 1.3 GHz case is ~10 times higher.
- Excitation of FPMs critical in both cases, but again worse in the 1.3 GHz case. Can be strongly influenced by layout choices (transition energies, cavity families).